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Original Article

Dry sliding wear investigation of Al6082/Gr metal matrix composites by response surface methodology

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ABSTRACT

The effect of graphite particles on the dry sliding wear behaviour of Al6082 alloy composites produced by conventional stir casting method has been investigated. The percentage of reinforcement was varied from 0% to 12% in a step of 3. The result showed that with the addition of graphite particles micro- and macro-hardness reduced by 11.11% and 10.44%, respectively. The tribological behaviour of composites was investigated by pin on disc apparatus. Percentage reinforcement, load, sliding speed and sliding distance were taken as the process variable. Response surface methodology has been used to plan and analyze the experiment. Results showed that sliding distance is the most influential factor and load is the factor which affects the wear least.

1. Introduction

Every automotive industry in the recent time keen to manufacture the parts which are light in weight with excellent tribological properties especially in the manufacturing of hydraulic brake system components where wear resistance is given as the most important consideration. Aluminium, which is light in weight, can be used as a main matrix element in the fabrication of composite materials and these manufactured composite are termed as aluminium matrix composites (AMCs). Owing to technology growth, there is enlarged demand for an economical, low weight, harder, stronger and energy saving material in the aircraft, space, defense and automotive applications. AMCs found application in these areas [1,2]. Since last four to five decades there is wide exploration and pioneering development in the field of composite materials and in the past few years, most of the researchers tried to reinforce monolithic metal and alloy with ceramic phase to enhance their properties [3]. AMCs when

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Table 1 – Chemical composition of AA6082-T6.

Element	Al	Cu	Mg	Si	Fe	Ni	Mn	Zn	Pb	Tin	Ti	Cr	Vn
Content %	97.14	0.038	0.690	1.16	0.258	0.04	0.580	0.027	<0.001	0.006	0.048	0.042	<0.01

compared to unreinforced alloy have better properties such as high strength, high stiffness, high wear resistance and high thermal stability, furthermore these properties can be adapted to a specific requirement [4]. Graphite is a soft reinforcement which prevents metal to metal contact by forming a thin layer of Gr particle because of its self-lubricating properties, so Al–Gr composites have better wear resistance than conventional aluminium alloy. Liu et al. [5] observed a linear relationship between wear volume and load for Al–Gr composites manufactured by laser processed method and revealed that Gr particles formed a thin lubricating film, which significantly improved the wear resistance of composites. Lin et al. [6] observed for Al–Gr composite when Gr particles increased from 0% to 6% wear has been reduced, this may be due to graphite formed a thin lubricating film which prevented direct contact of sliding surfaces and reduced ploughing effects of Al chips. Hassan et al. [7] manufactured the Al–Gr composite and reported decrease in hardness with increase in % reinforcement of Gr due to increased porosity. Akhlaghi and Bidaki [8] fabricated Al2024 composites with varying amount of Gr (5–20%) by in situ powder metallurgy process and found that an increase in Gr content reduced the coefficient of friction, hardness and fracture toughness of composites. Ted and Tsao [9] concluded that the addition of Gr resulted in reduced wear of Al–Gr composites compared to Al alloy. Jha et al. [10] reported that wear rate of AA6061–Gr composites increased with increasing the amount of graphite reinforcement by powder metallurgy process. Liu et al. [11] reported that both the wear and friction of Al2014–Gr composites manufactured by squeeze casting decreased when the volume fraction of graphite reached upto 50%. Rohatgi et al. [12] reported that aluminium matrix composites reinforced with hard particles like SiC showed higher wear and coefficient of friction than soft particles like Gr. Baradeswaran and Perumal [13] concluded that AA7075/Gr composites manufactured by liquid casting technique had better wear resistance than pure aluminium matrix and wear resistance increased with increased amount of Gr whereas hardness and tensile strength decreased.

1.1. *Selection of fabrication method*

There are a number of manufacturing methods available to fabricate AMCs like powder metallurgy, ball milling, friction stir processing, pressure-less infiltration method, etc., but conventional stir casting is an attractive and economical process and can produce complex shape products and offers a wide range of material and processing condition [14–16]. It offers better matrix particles bonding due to stirring action of particles into the melts. As a cost effective process stir casting can be used in mass production of composite manufacturing at industrial scale. Owing to all these advantages, stir casting is employed in present research for the development of composites.

1.2. *Selection of metal matrix*

Aluminium 6082 is a medium strength alloy with excellent corrosion resistance and manganese present in it controls the grain structure, which results into a stronger alloy and its application are in the field of high stress application, bridges, trusses, cranes, transport application, etc. Amount of silicon in 6082 is high, which increases its wear resistance and copper is low so it is highly wear and corrosion resistant. The properties of AA6082 can be further improved if it is alloyed properly with reinforcement like Gr to enhance its wear resistance so that the developed composites can be used in tribological applications where wear resistance is of main concern.

1.3. *Aim of research*

A limited research work or almost nil has been reported on wear behaviour of Gr reinforced composites by taking Al6082 metal matrix containing wide range of reinforcements. In this research the dry sliding wear behaviour of AA6082/Gr composite (by varying Gr particles range from 0% to 12% by weight) produced in an inert atmosphere using conventional stir casting are presented.

2. Research methodology

2.1. *Development of composite by stir casting process*

The proposed Al6082/Gr composites required for the analysis are fabricated by stir casting. AA6082-T6 is used as the matrix alloy and details of its composition after spectro-Lab test is given in Table 1. Table 2 provides the details of Gr particulates, which are used as reinforcement. A batch of 1000 g of aluminium alloy was measured and put in the graphite crucible and was melted at 900 °C using an electric furnace. To obtain homogeneous distribution of reinforcement in the melt proper stirring is required. The melt was stirred with the help of a mechanical stirrer to form a fine vortex for 10 min [17,18]. The Gr ceramic powder was preheated to a temperature of 500 °C so that their surface oxidized, this preheated ceramic powder was added at a constant feed rate into vortex. Argon gas was supplied into the melt during operation to provide an inert atmosphere. After stirring the molten mixture, it was poured into the mould of dimension 12 mm diameter and 55 mm length. Argon gas was supplied until the

Table 2 – Details of Reinforcement.

Reinforcement	Hardness (GPa)	Grain size (μm)	Density (g/cm^3)
Gr	0.25	50	2.2

Table 3 – Factors and their level in CCD experimental plan.

Factors	Designation	Levels				
		−2	−1	0	+1	+2
Reinforcement (%)	*R*	0	3	6	9	12
Load (N)	*L*	15	30	45	60	75
Sliding speed (m/s)	*S*	0.4	0.8	1.2	1.6	2.0
Sliding distance (m)	*D*	400	800	1200	1600	2000

entire melt was poured into the preheated permanent mould at 250 °C. The manufactured composite was allowed to solidify in atmospheric air and was taken out from the mould after solidification. The AMCs having different weight percentage (3, 6, 9 and 12 wt.%) of Gr ceramic powder were manufactured by the same procedure.

2.2. *Micro-hardness measurement*

The micro-hardness of composites was measured using Vickers hardness tester (MITUTOYO-MVK-H1) at a load of 500 g applied for a duration of 15 s at 20 different locations on all specimens.

2.3. *Macro-hardness measurement*

The macro-hardness of the composites was evaluated by using a Brinell hardness tester (model 7KB3000) at a load of 500 kg applied for a duration of 15 s at 10 different locations.

2.4. *Wear test*

Wear test specimens of dimension diameter 8 mm and length 35 mm were prepared. The end surfaces of the wear test specimens were properly cleaned and then polished with abrasive paper of grade 400, 600 and 1000, respectively. The wear test has been performed on pin on disc apparatus. The disc of the pin on disc is made of EN31 steel having surface roughness 0.1. The pins and disc were cleaned properly with the help of acetone before and after wear test. The wear was measured by weight loss, taking weight of the wear pins before and after wear test to an accuracy of 0.0001 g.

2.5. *Response surface methodology*

The vast amounts of data have been generated by the traditional approach of experiment design in which one factor is varied at a time (load, sliding speed, etc.). In this approach, it is difficult to evaluate the combined effects of applied factors. This is the main reason why load has always been considered first in wear research, whilst other factors, e.g. reinforcement, sliding distance and their combined effects (load and reinforcement, load and speed, etc.), which may also be important, have not been given the attention they deserve. The advantage of the statistical method is obvious [19]. Thus, RSM (response surface methodology) with full factorial design of experiments with five levels of each factor has been used in the present study. According to Rabinowicz's classic theory [20] that claims applied load and hardness (depends upon composition) of materials are the most important factors affecting the wear process, therefore, both these factors were considered along with the sliding speed and sliding distance in this study. Thus, four factors, % reinforcement, load, sliding speed and sliding distance, were used in the present study. These factors were designated as *R* (% reinforcement), *L* (load), *S* (sliding speed) and *D* (sliding distance), respectively. The coded value of upper, middle and lower level of these factors is designated by +2, +1, 0, −1, and −2, respectively. Table 3 shows the factor and their level used in the analysis. The experimental design matrix for different runs and various factors with their actual and coded value (in parentheses) is shown in Table 4.

The relation between the actual and coded value of a factor is shown below:

$$\text{Coded value} = \frac{\text{Actual test conditions} - \text{Mean test conditions}}{\text{Range of test conditions}/2}$$

The rotatable central composite design (CCD) was used in the present investigation. The design expert 6.0.8 software was used for analysis of data obtained. The wear tests were performed according to design matrix (Table 4) and weight loss was the measured as response used to evaluate dry sliding wear behaviour Al/Gr composites.

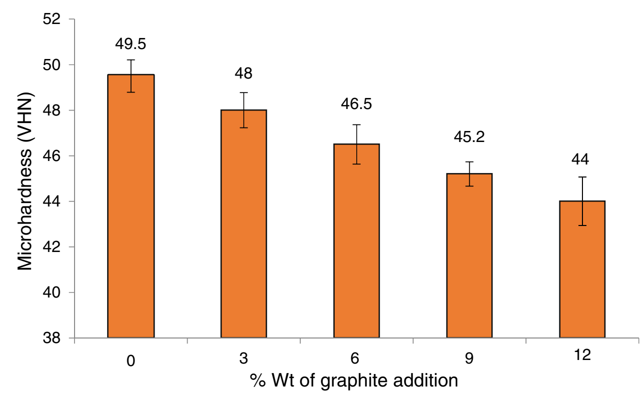

Fig. 1 – Variation of micro-hardness with weight percentage of Gr addition.

3. Result and discussion

3.1. *Hardness result*

The hardness value decreased (both micro and macro) as the percentage Gr addition increased in the alloy (Figs. 1 and 2) this may be due to low density of graphite as they are soft reinforcement and float in the melt and resulted into weak bonding between the matrix and Gr particles, which resulted into non uniform distribution of graphite particles, which

Table 4 – Design matrix and various factors with their actual and coded value (in parentheses).

Run no.	Process parameters				Wear (g)
	Reinforcement (R)	Load (L)	Sliding speed (S)	Sliding distance (D)	
1	3 (−1)	30 (−1)	0.8 (−1)	800 (−1)	0.0076
2	9 (+1)	30 (−1)	0.8 (−1)	800 (−1)	0.006
3	3 (−1)	60 (+1)	0.8 (−1)	800 (−1)	0.008
4	9 (+1)	60 (+1)	0.8 (−1)	800 (−1)	0.0058
5	3 (−1)	30 (−1)	1.6 (+1)	800 (−1)	0.0036
6	9 (+1)	30 (−1)	1.6 (+1)	800 (−1)	0.0025
7	3 (−1)	60 (+1)	1.6 (+1)	800 (−1)	0.0052
8	9 (+1)	60 (+1)	1.6 (+1)	800 (−1)	0.0006
9	3 (−1)	30 (−1)	0.8 (−1)	1600 (+1)	0.0161
10	9 (+1)	30 (−1)	0.8 (−1)	1600 (+1)	0.0146
11	3 (−1)	60 (+1)	0.8 (−1)	1600 (+1)	0.0182
12	9 (+1)	60 (+1)	0.8 (−1)	1600 (+1)	0.0172
13	3 (−1)	30 (−1)	1.6 (+1)	1600 (+1)	0.0095
14	9 (+1)	30 (−1)	1.6 (+1)	1600 (+1)	0.0081
15	3 (−1)	60 (+1)	1.6 (+1)	1600 (+1)	0.0152
16	9 (+1)	60 (+1)	1.6 (+1)	1600 (+1)	0.0132
17	0 (−2)	45 (0)	1.2 (0)	1200 (0)	0.0115
18	12 (+2)	45 (0)	1.2 (0)	1200 (0)	0.0077
19	6 (0)	15 (−2)	1.2 (0)	1200 (0)	0.0051
20	6 (0)	75 (+2)	1.2 (0)	1200 (0)	0.0098
21	6 (0)	45 (0)	0.4 (−2)	1200 (0)	0.0123
22	6 (0)	45 (0)	2 (+2)	1200 (0)	0.0075
23	6 (0)	45 (0)	1.2 (0)	400 (−2)	0.0018
24	6 (0)	45 (0)	1.2 (0)	2000 (+2)	0.0199
25	6 (0)	45 (0)	1.2 (0)	1200 (0)	0.0091
26	6 (0)	45 (0)	1.2 (0)	1200 (0)	0.0071
27	6 (0)	45 (0)	1.2 (0)	1200 (0)	0.0068
28	6 (0)	45 (0)	1.2 (0)	1200 (0)	0.0071
29	6 (0)	45 (0)	1.2 (0)	1200 (0)	0.0089
30	6 (0)	45 (0)	1.2 (0)	1200 (0)	0.006

in-turns results into decrease in hardness with increase in weight percentage of Gr particles. These results are in line with previous investigations [7,8,13].

3.2. *Development of wear model by RSM*

In RSM the input process parameters are represented in the form of response in the quantitative form as:

$$Y = f(X_1, X_2, X_3, \ldots, X_n) \pm \varepsilon \tag{1}$$

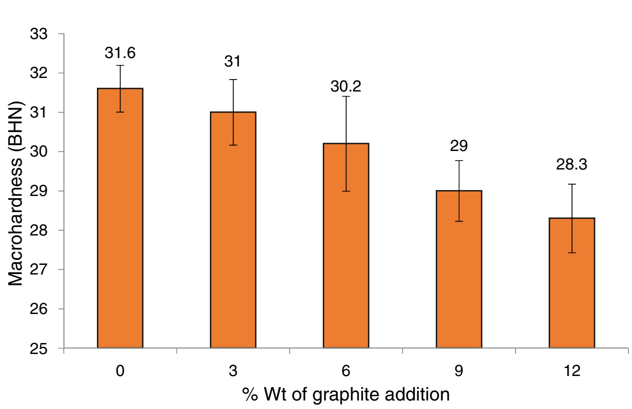

Fig. 2 – Variation of macro-hardness with weight percentage of Gr addition.

where Y is the response (yield), f is the response function, ε is the experimentation error, and $X_1, X_2, X_3, \ldots, X_n$ are independent input process parameters.

Expected response Y is plotted with the help of input process parameter to obtain a response surface. The response function 'f', which is not known to us, is very complicated to determine. RSM is used for this purpose, the main aim of which is to approximate f by determining a range of independent input process parameters by applying a lower order polynomial equation. If the model is appropriate and suitable then the response of the model can be represented by a linear function in terms of independent process parameters, then the response represented in Eq. (1) can be written as

$$Y = C_0 + C_1X_1 + C_2X_2 + \ldots C_nX_n \pm \varepsilon \tag{2}$$

However, there may be a possibility of appearance of curvature in the response system made then a higher order polynomial, i.e., quadratic equation will be used to represent the response equation and following equation may be used.

$$Y = C_0 + \sum_{i=1}^{n} C_iX_n + \sum_{i=1}^{n} d_iX_i^2 \pm \varepsilon \tag{3}$$

The central composite design (CCD) was used in this experimental study. Significance testing of the coefficients, adequacy of the model and analysis of variance was carried

Table 5 – ANOVA table for wear rate (after backward elimination).

Source	Sum of squares	Degree of freedom	Mean square	f-value	Prob. > f
Model	6.738×10^{-4}	8	8.423×10^{-5}	73.38	<0.0001
Reinforcement (R)	2.204×10^{-5}	1	2.204×10^{-5}	19.20	0.0003
Load (L)	2.563×10^{-5}	1	2.563×10^{-5}	22.33	0.0001
Sliding speed (S)	8.513×10^{-5}	1	8.513×10^{-5}	74.16	<0.0001
Sliding distance (D)	4.950×10^{-4}	1	4.950×10^{-4}	431.28	<0.0001
A^2	7.823×10^{-6}	1	7.823×10^{-6}	6.82	0.0163
C^2	1.020×10^{-5}	1	1.020×10^{-5}	8.89	0.0071
D^2	1.981×10^{-5}	1	1.981×10^{-5}	17.26	0.0004
BD	1.521×10^{-5}	1	1.521×10^{-5}	13.25	0.0015
Residual	2.410×10^{-5}	21	1.148×10^{-6}		
Lack of fit	1.652×10^{-5}	16	1.033×10^{-6}	0.68	0.7454
Pure error	7.580×10^{-6}	5	1.516×10^{-6}		
Cor total	6.979×10^{-4}	29			

out by using Design Expert Software to find out the significant factors, square terms and interactions affecting the response (dry sliding wear).

The analysis of variance (ANOVA) is shown in Table 5. The analysis of variance (ANOVA) shows the significance of various factors and their interactions at 95% confidence interval. ANOVA shows the "Model" as "Significant" while the "Lack of fit" is "Not significant", which are desirable from a model point of view. The probability values <0.05 in the "Prob. > F" column indicates the significant factors and interactions. The main factors and their interactions are included in the final dry sliding wear model while the insignificant interactions are excluded from the wear model. % Reinforcement (R), load (L), sliding speed (S) and sliding distance (D) are the significant factors while load–sliding distance (LD) is the significant interactions. Quadratic terms of percentage reinforcement, sliding speed and sliding distance also have significant influence on the dry sliding wear of composites manufactured.

After eliminating the non-significant terms, the dry sliding wear model generated in terms of coded and actual factor values (Eqs. (4) and (5) respectively) is given below:

In coded parameters:

$$\begin{aligned} Wear\ (g) = {} & 7.488 \times 10^{-3} - 9.583 \times 10^{-4} \times A + 1.033 \times 10^{-4} \\ & \times B - 1.883 \times 10^{-3} \times C + 4.542 \times 10^{-3} \times D + 5.286 \\ & \times 10^{-4} \times A^2 + 6.036 \times 10^{-4} \times C^2 + 8.411 \times 10^{-4} D^2 \\ & + 9.750 \times 10^{-4} \times B \times D \end{aligned} \tag{4}$$

In actual parameters:

$$\begin{aligned} Wear\ (g) = {} & 0.022221 - 1.02421 \times 10^{-3} \times \text{Reinforcement}\ (R) \\ & - 1.26111 \times 10^{-4} \times \text{Load}\ (L) - 0.013762 \\ & \times \text{Sliding Speed}\ (S) - 8.57440 \times 10^{-6} \\ & \times \textit{Sliding}\ \text{Distance}\ (D) + 5.87302 \times 10^{-5} \\ & \times \text{Reinforcement}\ (R)^2 + 3.77232 \times 10^{-3} \\ & \times \text{Sliding Speed}\ (S)^2 + 5.25670 \times 10^{-9} \\ & \times \text{Sliding Distance}\ (D)^2 + 1.62500 \times 10 - 7 \\ & \times \text{Load}\ (L) \times \text{Sliding Distance}\ (D) \end{aligned} \tag{5}$$

The value of R^2 and adjusted R^2 is over 95%. This means that regression model provides a tremendous clarification of the relationship between input variables (process parameters) and output response (dry sliding wear). The associated p-value for the model is lower than 0.05 (i.e. $\alpha = 0.05$ or 95% confidence) indicates that model is considered to be statistically significant.

3.3. *Validity of the wear model and confirmation experiments*

The validity of the dry sliding wear model was evaluated by conducting dry sliding wear test on composites at different values of the experimental factors such as % reinforcement (R), load (L), sliding speed (S) and sliding distance (D). As the equation of response for the model is derived from quadratic regression fit, so to confirm their validity confirmation test must be performed. The independent variable selected for the confirmation experiments must lie within the ranges for which equations were derived. The three confirmation experiments were performed for wear rate at the condition of independent process parameter provided by quadratic model. The data from the confirmation experiments and their comparison with the predicted designed for wear rate are listed in Table 6. From the table it can be observed that calculated error is small. The error between experimental and predicted values is small which confirms the experimental conclusion.

3.4. *Effect of individual variables on wear rate*

The effect of individual factors on dry sliding wear is shown in Fig. 3(a)–(d). The effect of percentage reinforcement (R), load (L), sliding speed (S), sliding distance (D) and that of interactions between load (L) and sliding distance (D) on dry sliding wear is given in Eq. (4), which exhibits the dry sliding wear in terms of coded value and Eq. (5) in terms of actual values of factors and their interactions. However, the effect of individual factors is discussed by considering Eq. (4) because all the factors are at same level. The constant 7.488×10^{-3} in Eq. (4) indicates the overall mean of the dry sliding wear of composite under all the test conditions. This equation further indicates that the coefficient 9.583×10^{-4} associated with percentage reinforcement is negative, which signifies a decrease

Table 6 – Confirmation test and their comparison with the result.

Exp. no.	Process parameters				Wear (g)		
	% Reinforcement (R)	Load (L)	Sliding speed (C)	Sliding distance (D)	Exp.	Predicted	Error (%)
1	4	60	0.9	1500	0.0165	0.0158	4.24
2	8	40	1.6	900	0.0031	0.0028	9.68
3	3	35	1.5	1500	0.0110	0.0106	3.63

of wear with an increase of percentage reinforcement Fig. 3(a). This is attributed due to the presence of Gr particles, which as a soft lubricant formed a layer between the sliding surfaces and prevented the contact of sliding surfaces [6]. The effect of load, sliding speed and sliding distance on wear is shown in Fig. 3(b)–(d). The coefficient associated with load, sliding speed and sliding distance is 1.033×10^{-4}, 1.883×10^{-3} and 4.542×10^{-3}, respectively. This signifies that sliding distance has a more detrimental effect than the applied load and sliding speed on the wear of the composite. The effect of load on

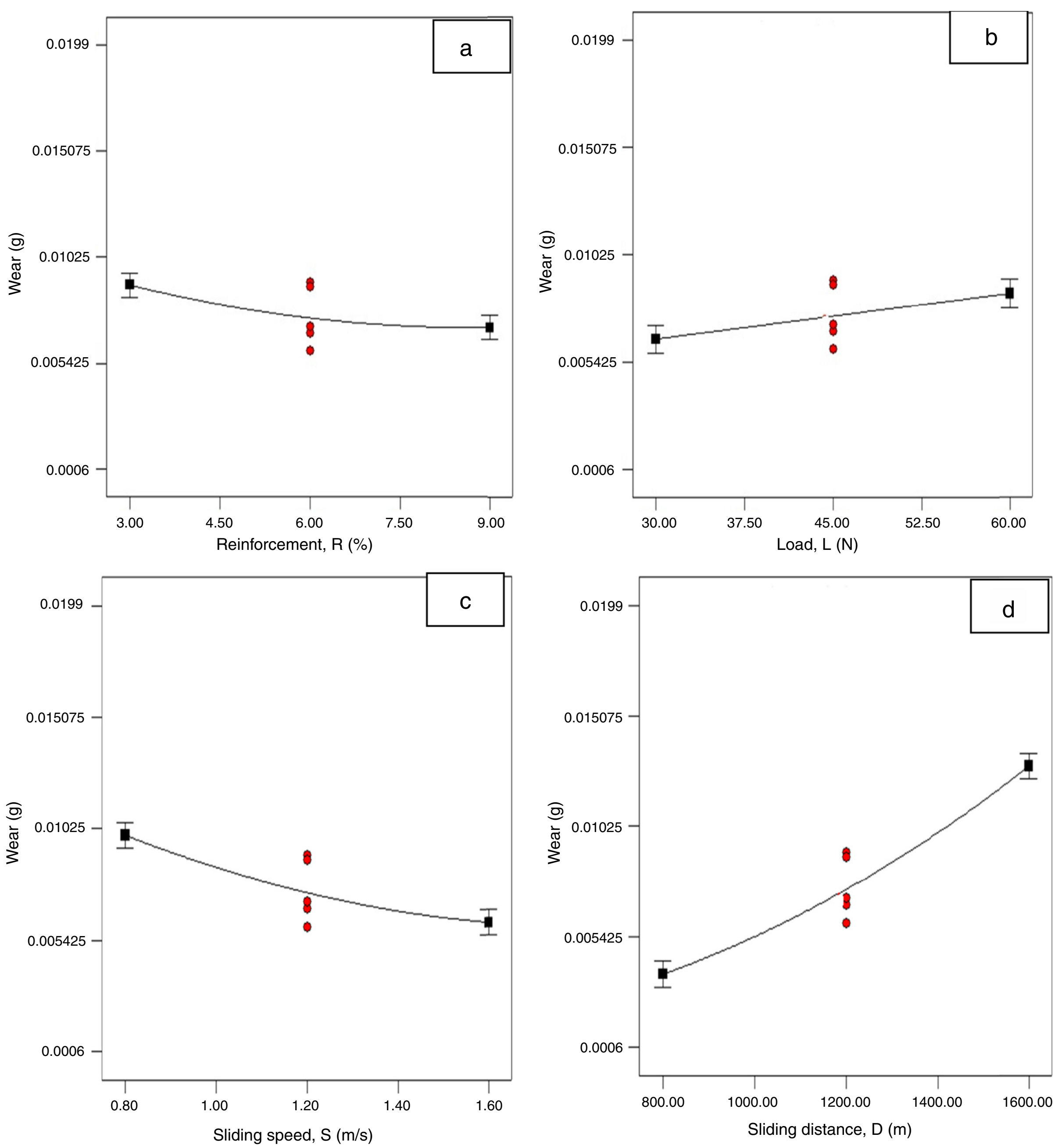

Fig. 3 – Effect of individual factors on dry sliding wear (a) percentage reinforcement, (b) load, (c) sliding speed, and (d) sliding distance.

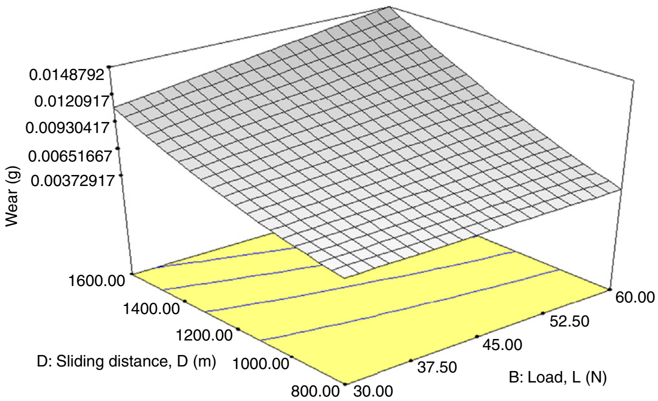

Fig. 4 – Effect of load and sliding distance interaction on wear.

wear is shown in Fig. 3(b) the wear increased with increase in load, which is due to the fact that with increase in load contact pressure increased on the sliding surfaces which resulted into increased wear at high load. The effect of sliding speed on the wear is shown in Fig. 3(c) where low as compared to sliding distance. The wear decreased with increased in sliding speed, which may be due to the fact that higher sliding speeds results in increase in temperature. This increase in temperature further leads to oxidation of the contact surfaces. The hard nature of oxides results in low wear of the composite. Also at higher sliding speed the time of interaction between sliding surface decreased which results in to low amount of material removed. The effect of sliding distance on the wear is shown in Fig. 3(d) where the wear increased with increase in sliding distance. This may be due to the fact contact area of sliding surface increased with increased in contact time which in turns increased wear of the composite.

3.5. *Interaction effect of the different variables*

Fig. 4 shows the effect of load and sliding distance (*LD*) on wear rate the hold condition for percentage reinforcement was 6% while that for sliding speed was 1.2 m/s. With the increase in load the wear increased as shown in Fig. 4. This may be due to the fact that with the increase in load keeping the sliding distance constant the high pressure is applied on the sliding surfaces, which results in increased wear of the composite and with increase in sliding distance keeping the load constant the wear rate of composite increased because at higher sliding distance the time of interaction between the sliding surfaces increased due to the amount of material removed increased. The combined effect of load and sliding distance increased the wear.

4. Conclusion

The Al6082/Gr composites were successfully fabricated by stir casting process and the hardness of composite decreased as compared to cast Al6082. The wear resistance of composite has been improved as compared to conventional AA6082 matrix. RSM is used for the empirical modelling of response, i.e. wear rate of composites and the following conclusion were drawn from the present investigation.

1. The micro-hardness of composites was decreased from 49.5 VHN to 44 VHN and macro-hardness from 31.6 BHN to 28.3 BHN, respectively, with respect to addition of weight percentage of Gr.
2. The wear rate of composites decreased with increasing sliding speed and percentage reinforcement and increased with increasing load, sliding distance.
3. The wear resistance of developed composites was lower than that of cast AA6082 at all combination of reinforcement, load, sliding speed and sliding distance.
4. ANOVA indicated that sliding distance is the most influential factor followed by sliding speed, percentage reinforcement and load on the wear rate of composites.
5. The interaction between load (*L*) and sliding distance (*D*) also has significant effect on the wear rate of composites.
6. The confirmation experiments showed that the error between experimental and predicted value of wear rate lies within range 3–10%.

Conflicts of interest

The authors declare no conflicts of interest.

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